

REAR PROJECTION DISPLAY

RELATED APPLICATIONS

The present U.S. Patent application is a continuation-in-part of, and claims the benefit of priority under 35 U.S.C § 120 to, U.S. Patent Application Ser. No. 10/222,083, entitled, "Rear Projection Display," filed on August 16, 2002.

FIELD

The invention relates to display devices. More specifically, the invention relates to a thin rear projection display device.

BACKGROUND

In order to provide a television with a screen size greater than approximately 40 inches a display device other than a direct view cathode ray tube (CRT) is typically used. As the screen size of a CRT increases, so too does the depth. It is generally accepted that for screen sizes greater than 40 inches direct view CRTs are no longer practical. Three alternatives exist for large screen (>40 inch screen size) displays: projection displays, plasma displays, and Liquid Crystal Displays (LCDs).

Current plasma and LCD displays are much more expensive than projection displays. Plasma and LCD displays are generally thin enough to mount on a wall, but can be heavy enough that mounting can be difficult. For example, current 42-inch plasma displays can weigh 80 pounds or more and 60-inch plasma displays can weigh 150 pounds or more. One advantage of plasma and LCD displays over current projection displays is that they are typically much thinner than current projection displays having the same screen size.

Projection displays, specifically rear projection displays, are typically more cost-effective than plasma displays. Projection displays may also consume too much space in a room to provide a practical solution for large screen needs. For example, typical 60-inch rear projection displays are 24 inches thick and can weigh 200 to 300 pounds.

5 Figure 1 illustrates a prior art rear projection display device. In general, display device 100 includes optical engine 140, projection lens 130, back plate mirror 120 and screen 110. Optical engine 140 generates an image to be projected on screen 110. Projection lens 130 projects the image from optical engine 140 on to back plate mirror 120, which reflects the image to screen 110. The size of display device 100 is proportional to the size of the image to be displayed on screen 110. Thus, for large
10 screen sizes (e.g., >60 inches), the overall size of display device 100 can be very large.

Fresnel lenses may be used to direct a projected image toward a viewer. Conventional rear projection display devices are thick because of surface reflections from the Fresnel surface. As the angle of incidence increases (on the flat side of the Fresnel)
15 the amount of light that is reflected from the air-plastic interface also increases, reducing image uniformity. A person of ordinary skill in the art is familiar with calculating Fresnel surface reflections.

Figure 2 illustrates a conventional rear projection display device 200 that is implemented with a Fresnel lens. Conventional rear projection display device 200
20 includes: optical engine 210, projection lens 220, Fresnel lens 230, and diffusion screen 240. The light impinging on the transmission surface of Fresnel lens 230 is roughly symmetric with respect to optical axis 250. A shortcoming of rear projection display

device 200 is that the grooves of Fresnel lens 230 are on the output side of Fresnel lens 230. It is not possible to bond diffusion screen 240 to Fresnel lens 230 because the grooves are facing diffusion screen 240.

SUMMARY

5 A display device includes a screen, a lens system that projects an image and a substantially planar back plate mirror to reflect the image to the screen. The back plate mirror is substantially parallel to the screen. In an embodiment of the invention, the screen is a Fresnel lens having a plurality of bumps on the output surface to reduce the visibility of a stray light image. In an alternative embodiment of the invention, the screen
10 is a Fresnel lens having a diffusion layer on the output side of the Fresnel lens to reduce the visibility of a stray light image.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings in which like reference numerals refer to
15 similar elements.

Figure 1 illustrates a prior art rear projection display device.

Figure 2 illustrates a conventional rear projection display device 200 that is implemented with a Fresnel lens.

Figure 3 illustrates one embodiment of an ultra-thin rear projection display device
20 with planar mirrors parallel to a screen.

Figure 4 illustrates a Fresnel lens with outlines of sections to be used for rear projection screens.

Figure 5 illustrates a cross-sectional profile view of a Fresnel lens having a groove angle of 39° .

Figure 6a illustrates a front view of a Fresnel lens having two zones each having a different groove angle.

5 Figure 6b illustrates a cross-sectional profile view of a two-zone Fresnel lens having a first zone with a groove angle of 35° and a second zone having a groove angle of 41° .

Figure 7 illustrates an input ray having a 60° input angle with a Fresnel lens having a face angle of 10° .

10 Figure 8 illustrates a profile cross-section view of a Fresnel lens design having two zones with different groove angles and transition regions for the zones.

Figure 9 illustrates a profile cross-section view of a selected portion of a Fresnel lens design.

15 Figure 10 illustrates one embodiment of a Fresnel lens having two zones on opposite sides of the lens with a transition region for the two zones.

Figure 11 illustrates one embodiment of a rear projection display device having a wide-angle lens.

Figure 12 illustrates rear projection display device 1200 and the potential problem of stray light.

20 Figure 13 illustrates rear projection display device 1300, with elements to reduce stray images.

Figure 14 illustrates an exemplary bump 1410 scattering light rather than coherently reflecting light.

Figure 15 illustrates an exemplary diffusion layer 1510 diffusing light that might otherwise form a stray image.

5 Figure 16 illustrates the relationship between face angle (γ) and output ray angle (β), according to an embodiment of the invention.

Figure 17 provides an exemplary illustration of face angle (γ) and output ray angle (β) varying as a function of radial distance from the center of a Fresnel lens, according to an embodiment of the invention.

10 Figure 18 is a front view of screen 1800.

Figure 19 illustrates rear projection display device 1900.

DETAILED DESCRIPTION

An ultra-thin rear projection display system is described. In the following description, for purposes of explanation, numerous specific details are set forth in order
15 to provide a thorough understanding of the invention. It will be apparent, however, to one skilled in the art that the invention can be practiced without these specific details. In other instances, structures and devices are shown in block diagram form in order to avoid obscuring the invention.

The ultra-thin rear projection display device described herein includes a wide-
20 angle lens system and one or more planar mirrors that are parallel to a screen on which an

image is to be displayed. In one embodiment, the screen that has multiple groove angles to provide better illumination than screens with a single groove angle.

As described in greater detail below, the screen can be a Fresnel lens having one or more groove angles. However, many other objects can operate as a screen for purposes of displaying an image. In general, any object that diffuses light can be used as a screen. For example, a wall, water or fog can be used as a screen.

Figure 3 illustrates one embodiment of an ultra-thin rear projection display device with planar mirrors parallel to a screen. As described in greater detail below, use of planar mirrors parallel to the screen as well as a wide angle projection lens having an optic axis that is perpendicular to the mirrors and the screen allows the ultra-thin rear projection display device to be thinner and simpler than prior art rear projection display devices. For example, an ultra-thin rear projection display device as described herein that is less than 7 inches thick can provide a 60-inch image.

In one embodiment, ultra-thin rear projection display device 300 includes screen 310, back plate mirror 320, intermediate mirror 330, lens system 340 and digital micromirror device (DMD) 350. Other components, for example, image generating components are not illustrated for reasons of simplicity of description. An image can be provided to DMD 350 in any manner known in the art. DMD 350 selectively reflects light from a light source (not shown in Figure 3) to lens system 340. Any type of display device known in the art can be used in display device 300. Other types of devices (e.g., microelectromechanical systems (MEMS), grating light valve (GLV), liquid crystal display (LCD), liquid crystal on silicon (LCOS)) can be used to provide an image to lens

system 340. In one embodiment, the mirrors are substantially parallel to the screen, which implies an alignment error of $\pm 10^\circ$. In one embodiment, the optic axis of the wide-angle lens system is substantially perpendicular to the screen, which also implies an alignment error of $\pm 10^\circ$

5 In one embodiment, DMD 350 is offset from the optic axis of lens system 340 such that only a portion (e.g., 50%, 60%, 40%) of the available lens field is used. The image from DMD 350 is projected by lens system 340 in the upper portion of the lens field to intermediate mirror 330, in an embodiment of the invention. The image is then reflected to back plate mirror 320 and finally to screen 310.

10 In an alternative embodiment of the invention, the image from DMD 350 is projected by lens system 340 in the lower portion of the lens field to intermediate mirror 330. In such an embodiment, wide-angle lens system 340 may be, at least partly, above intermediate mirror 330. Intermediate mirror 330, in turn, may be, at least partly above back plate mirror 320. The image is then reflected to back plate mirror 320 and finally to
15 screen 310.

 In order to project an image as described, lens system 340 is a very wide-angle lens system. In one embodiment, lens system 340 has a field angle of 152° or more; however, other lenses can be used. In general, the wider the angle of lens system 340, the thinner display device 300 can be made. Description of a suitable wide-angle lens system
20 is described in the above-referenced patent application, which is incorporated by reference.

Intermediate mirror 330 reflects the image to back plate mirror 320, which reflects the image to screen 310. In one embodiment, screen 310 is a Fresnel lens. Back plate mirror 320 is also a planar mirror and is parallel to screen 310 and perpendicular to the optic axis of lens system 340. Because the optic axis of lens system 340 is perpendicular to intermediate mirror 330 and both intermediate mirror 330 and back plate mirror 320 are planar and parallel to screen 310, the distortion caused by angled lenses and aspherical mirrors is absent in display device 300. This simplifies the design of display device 300 and reduces the cost and complexity of manufacturing.

Figure 4 illustrates a Fresnel lens with outlines of sections to be used for rear projection screens. Figure 4 provides a conceptual illustration of the sections of a Fresnel lens that can be used for various rear projection display devices. The Fresnel lens can be described with two angles. The face angle is defined as the angle of the surface of each individual groove through which light passes as it enters, or in the case of some refractive designs exits the Fresnel lens relative to the optic axis of the lens. The groove angle is the angle formed between the input face and the reflection face, or in the case of a refractive lens between the optical face of the groove and the non-optical face. Face angles and groove angles are more fully discussed below with reference to Figure 16.

In one embodiment, Fresnel lens 400 can have many concentric grooves having one or more predetermined groove angles. Techniques for manufacturing and using Fresnel lenses having a single groove angle are known in the art. In a rear projection display device in which the full lens field of the projection lens system is used, a center portion 420 of Fresnel lens 400 is used for the lens of the display device.

Dashed rectangle 420 provides an indication of a screen from the center portion of Fresnel lens 400. The size and shape of the portion of the lens to be used corresponds to the size and shape of the screen of the display device. For traditional rear projection displays, the center of section 420 to be used for a screen is the center of Fresnel lens 420.

When using an offset DMD (or other device) so that only a portion of the projection lens field is used, the section of Fresnel lens 400 used for a screen is correspondingly offset from the center of Fresnel lens 400. For example, if the top half of the projection lens field is used, the bottom edge of screen portion 410 passes through the center of Fresnel lens 400.

Figure 5 illustrates a cross-sectional profile view of a Fresnel lens 500 having a groove angle 510 of 39° . The lens of Figure 5 can be used with, for example, the display system of Figure 3. When used with a display system as illustrated in Figure 3 with an offset as described with respect to Figure 4, the groove angle of 39° provides a balance between diamond cutter structural integrity and lens performance.

As the groove angle increases the image projected to the bottom center of lens 500 becomes dark because rays pass through the lens without being reflected from the intended total internal reflection (TIR) surface on the exterior of the groove. As the groove angle decreases, the image projected to the top corners of lens 500 become dark because reflected rays are directed down and away from the viewer. Also, as the groove angle decreases, the tool used to manufacture lens 500 can become too weak to work effectively.

Figure 6a illustrates a front view of a Fresnel lens having two zones each having a different groove angle. The embodiment of Figure 6a illustrates two zones with two groove angles; however, any number of zones with corresponding groove angles can be used. The groove angle of a lens can vary continuously. Also, while the example of
5 Figure 6a illustrates circular regions, other shapes can also be used.

In one embodiment, interior region 620 has grooves of approximately 35° ; however, other groove angles can also be used. When used for large screens, a Fresnel lens with a single groove angle throughout provides non-uniform illumination. In one embodiment, outer region 610 has grooves of approximately 41° ; however, other groove
10 angles can also be used. In alternate embodiments, interior region 620 and outer region 610 can provide any combination of refraction and/or reflection lenses. In one embodiment, the projector side of lens 600 has grooves and the viewer side is planar. In an alternate embodiment, lens 600 has grooves on both sides.

Figure 6b illustrates a cross-sectional profile view of a two-zone Fresnel lens
15 having a first zone with a groove angle of 35° and a second zone having a groove angle of 41° . The lens of Figure 6b can be used with, for example, the display system of Figure 3. The lens of Figure 6b provides improved uniformity as compared to the lens of Figure 5.

In one embodiment, the grooves of zone 620 provide a refractive lens and the
20 grooves of zone 610 provide a total internal reflection (TIR) lens. The refractive and reflective zones of lens 600 can be on the same side of the lens (e.g., the projector side) or the refractive and reflective zones of lens 600 can be on opposite sides (e.g., reflective

on the projector side and refractive on the viewer side). An example of an embodiment of the invention wherein the refractive and reflective zones of a lens are on opposite sides is described below with reference to Figure 10. As described in greater detail below, transition regions can be used to reduce or even eliminate image artifacts caused by transitions between zones. For a double-sided lens, two single-sided lenses can be aligned and the planar sides of each lens can be bonded together. Alternatively, one side of the lens can be manufactured, for example, by a curing process and additional grooves can be formed directly on the opposite side of the lens by the same process.

Figure 7 illustrates an input ray having a 60° input angle with a Fresnel lens having a face angle of 10° . For steep angles of input light (e.g., greater than about 45°) it is possible to design face angles of the grooves such that all light enters the Fresnel lens and reflects off of reflection face and travels directly toward the viewer. For example, input light 720 passes through groove face 700 and is slightly refracted. Refracted light 730 is reflected by reflection face 710 toward a viewer (not shown in Figure 7). For most applications, reflected light 740 is directed toward the viewer.

As the angle of the input light decreases, there is an angle at which the refracted light misses reflection face 710. This occurs, for example, at the bottom center of the screen at the grooves closest to the Fresnel center. This light is lost and travels through the Fresnel structure creating either a ghost image or a reduction in contrast. The lost light reduces contrast at the bottom center of the screen area (and possibly everywhere depending on where the mirrors are with respect to the screen).

One technique to reduce ghost rays and improve contrast in these areas is to change the reflection face angle such that, instead of directing light toward the viewer, the lens is designed to collect as much light as possible. As a consequence, the reflected light ray 740 travels downward. This improves the contrast of the displayed image, but the downward light does not get redirected to viewer as well and appears dark.

The face angles can be designed so that light from the top corners of the screen, where the input rays are steep, is reflected slightly toward the center of the lens to improve perceived brightness at the corners of the image. An example of an embodiment of the invention in which light from the top corners of the screen is reflected toward the center of the lens is more fully described below with reference to Table 1, Equation 2, Table 2, and Figure 17.

Figure 8 illustrates a profile cross-section view of a Fresnel lens design having two zones with different groove angles and a transition region between the zones. Lens 800 is illustrated with only a small number of grooves, zones and regions. This is for simplicity of description. A Fresnel lens can be used that has any number of grooves, zones, and/or regions.

As used herein, a “zone” is an area of a Fresnel lens having a particular groove angle (when the groove angle is not continuously variable). A “region” is an area of a Fresnel lens in which the face angle (γ) is defined by a single equation. A zone can include multiple regions. In one embodiment, one or more transition regions are included at zone boundaries in order to provide a smooth zone transition.

In one embodiment, the equation, F , that defines the face angle, which can be a function of radius, r , for a first region and the equation, G , that defines the face angle for a second region, are equal at the region boundary. In other words, $F(r_1) = G(r_1)$ where r_1 is the region boundary. Further, the first derivative of the equation that defines the face angle for a region is equal to the first derivative of equation that defines the face angle at the region boundary. In other words, $F'(r_1) = G'(r_1)$ where r_1 is the region boundary. This requirement provides for a transition that is not seen because the change in face angle is smoothly continuous.

Figure 9 illustrates a profile cross-section view of a Fresnel lens design. In one embodiment, the following equations describe the various angles of the Fresnel lens design. Alternative angle relationships can also be used. In the equations that follow, θ_6 is the input angle, or the angle of input ray 920 from horizontal; γ is the face angle, or the angle of refraction face 910 from horizontal; δ is the reflection face angle, or the angle of reflection face 900 from horizontal; ρ is the refracted ray angle, or the angle of refracted ray 930 from horizontal; θ_2 is the reflected ray angle, or the angle of reflected ray 950 from horizontal; and β is the output ray angle, or the angle of output ray 960 from horizontal.

In one embodiment, the following equations are used to determine the angles to be used for various regions. For a fixed peak angle (peak angle $k = \gamma + \delta$), the face angle can be calculated to create a Fresnel lens with no ghost rays near the bottom center and the face angles are modified to increase throughput.

For a two region embodiment, the inner region can be a lossless system defined by:

$$F(R, \gamma) := \left[\frac{\tan(\gamma) \cdot (\tan(\gamma) + 2 \cdot \tan(k - \gamma)) + \tan\left(\frac{\pi}{2} - \gamma - \arcsin\left(\frac{\cos\left(\arctan\left(\frac{R}{fl}\right) + \gamma\right)}{n}\right)\right) \cdot \tan(k - \gamma)}{\tan\left(\frac{\pi}{2} - \gamma - \arcsin\left(\frac{\cos\left(\arctan\left(\frac{R}{fl}\right) + \gamma\right)}{n}\right)\right) - \tan(k - \gamma)} - \frac{R}{fl} \right]$$

where n is the refractive index of the Fresnel lens material, k is the groove angle, R is the radius from the center of the Fresnel lens, and fl is the focal length of the Fresnel lens. Outer regions are defined by:

$$F2(R, \gamma) := \frac{\pi}{2} - \gamma - \arcsin\left(\frac{\cos\left(\arctan\left(\frac{R}{fl}\right) + \gamma\right)}{n}\right) - 2(k - \gamma) - \theta_2$$

Figure 10 illustrates an embodiment of a Fresnel lens having two zones with grooves on both sides of the lens and a transition region for the two zones. Fresnel lens 1090 includes two zones: a refractive zone and a reflective zone, as well as a transition region between the two zones. In alternate embodiments, lens 1090 can have one or more zones on a single side.

In one embodiment, Fresnel lens 1090 includes an inner zone that is a conventional refractive Fresnel lens design 1000. The inner zone may include the center of lens 1090 extending outward until the outer zone becomes more efficient than the inner zone. Fresnel lens 1090 further includes an outer zone that is a total internal reflection Fresnel design 1020. The outer zone directs more light toward the viewer than if the refractive design of the inner zone were to extend to the edge of the lens.

In order to reduce, or even eliminate, discontinuities between the refractive and the reflective portions of lens 1090, transition region 1010 is included. In one embodiment, in transition region 1010, the light rays internal to Fresnel lens 1090 change gradually from the upward angle of the refractive design to the horizontal angle of the reflective design. The gradual change reduces image discontinuities due to overlapping rays.

Figure 11 illustrates one embodiment of a rear projection display device having a wide-angle lens. Display device 1100 includes screen 1110, wide-angle lens system 1120 and DMD 1130. In one embodiment, screen 1110 is a Fresnel lens as described in greater detail above.

An image is generated and provided by optical engine components (not shown in Figure 11) that are known in the art and directed to wide-angle lens system 1120 via DMD 1130. In alternate embodiments, DMD 1130 can be replaced by other components, for example, microelectromechanical systems (MEMS), grating light valves (GLV), liquid crystal display (LCD), liquid crystal on silicon (LCOS), etc. In one embodiment, the optic axis of DMD 1130 is aligned with the optic axis of wide-angle lens system 1120 so that the full lens field is used to project the image to screen 1110. In alternate embodiments, the optic axis of DMD 130 can be offset from the optic axis of wide-angle lens system 1120. Use of a Fresnel lens as described above provides a thinner system with better brightness uniformity.

DIFFUSING STRAY LIGHT

Figure 12 illustrates rear projection display device 1200 and the potential problem of stray light. Rear projection display device 1200 includes screen 1210, back plate mirror 1220, intermediate mirror 1230, wide-angle lens system 1240, and digital micromirror device (DMD) 1250. DMD 1250 and wide-angle lens system 1240 project an image onto intermediate mirror 1230. Intermediate mirror 1230 reflects the projected image to back plate mirror 1220. Light reflected from back plate mirror 1220 may produce a desired image (e.g., ray 1254) and an undesirable image (e.g., stray rays 1258, 1260, and 1262). For example, if light travels the path defined by reference numeral 1252, it may produce desired ray 1254.

The angular surfaces of screen 1210 (e.g., the flat output surface) act as fairly good mirrors and coherently reflect some of the light that impinges on the surfaces. Light that is coherently reflected from the angular surfaces of screen 1210 may produce objectionable stray images. For example, light may travel the path defined by reference numerals 1252, 1266, 1268, and 1270 to produce stray ray 1258. Similarly, light may travel the path defined by 1252 and 1274 to produce stray ray 1262. A third example of the path “stray light” may take is shown by reference numerals 1252, 1276, 1278, and 1280 to produce stray ray 1260. A person of ordinary skill in the art appreciates that stray images may be produced by light traveling paths other than the exemplary paths shown in Figure 12.

Figure 13 illustrates rear projection display device 1300, with elements to reduce stray images. Rear projection display device 1300 may include more components than

those shown in Figure 13 or a subset of the components shown in Figure 13. It is not necessary, however, that all of these generally conventional components be shown in order to disclose stray light reduction.

In one embodiment, rear projection display device 1300 includes Fresnel lens 1310, back plate mirror 1320, intermediate mirror 1330, wide-angle lens system 1340, and digital micromirror device (DMD) 1350. Other components, for example, image generating components are not illustrated for reasons of simplicity of description. Fresnel lens also includes bumps 1370, diffuser 1380, and/or diffusion layer 1390.

Bumps 1370 help to reduce stray light visibility by scattering the stray light in many different directions. In some embodiments, bumps 1370 are affixed to the output side of Fresnel lens 1310. In alternative embodiments, bumps 1370 are formed on the surface of (e.g., are of unitary construction with) Fresnel lens 1310. In such embodiments, bumps 1370 may be formed by a curing process (e.g., an ultra violet (UV) curing process). Curing processes, including UV curing processes, are well known in the art. In yet other alternative embodiments, bumps 1370 may be formed by abrading a surface of Fresnel lens 1310 (e.g., abrading the output surface of Fresnel lens 1310).

Bumps 1370 are typically formed from translucent materials such as plastic or glass. In some embodiments, bumps 1370 are formed from the same material as Fresnel lens 1310. In alternative embodiments, bumps 1370 are formed from a different material than the material used to form Fresnel lens 1310.

In an embodiment, bumps 1370 are lenticular bumps. The term lenticular bump broadly refers to a bump having a convex cylinder shape. In alternative embodiments,

bumps 1370 are two-dimensional hills that are regularly or randomly distributed across the output side of Fresnel lens 1310. In an embodiment, at least one bump 1370 (e.g., 1370A) has a different size and/or shape than another bump (e.g., 1370B).

Fresnel lens 1310 may include diffuser 1380 to reduce stray light. Diffuser 1380 is typically formed from a translucent material such as plastic or glass. In an embodiment of invention, diffuser 1380 is formed by adding beads (e.g., white and/or tinted beads) to the material from which Fresnel lens 1310 is formed, while that material is in a liquid state. In such an embodiment, diffuser 1380 is said to be “of unitary construction with” Fresnel lens 1310.

The optical qualities of diffuser 1380 may be carefully selected so that light passing through diffuser 1380 a single time is not significantly altered. In contrast, light passing through diffuser 1380 multiple times is scattered in many directions to reduce the likelihood that it will interfere with the image quality of ultra-thin rear projection display device 1300.

Diffusion layer 1390 provides an alternative (and/or complimentary) mechanism for reducing stray light in an embodiment of the invention. The characteristics of diffusion layer 1390 are similar to those of diffuser 1380. For example, diffusion layer 1390 is typically formed from a translucent material designed to scatter light that passes through it more than once. Since diffusion layer 1390 is thin and close to the image surface, stray light is diffused without significantly reducing the sharpness of a displayed image.

Diffusion layer 1390 is affixed to the output surface of Fresnel lens 1310, in an embodiment. In alternative embodiments, diffusion layer 1390 is formed in a curing process (e.g., UV curing) on a surface of Fresnel lens 1310. In an exemplary embodiment, diffusion layer 1390 is approximately 0.8 millimeters thick (+/- 10 percent).

5 In alternative embodiments, diffusion layer 1390 may be thinner or thicker than 0.8 millimeters and may have a different tolerance (e.g., +/- 3 %, +/- 5 %, +/- 12 %, +/- 15 %, etc.)

In an embodiment, Fresnel lens 1310 includes one of diffuser 1380, diffusion layer 1390, and bumps 1370. In an alternative embodiment, Fresnel lens 1310 includes a
10 combination of diffuser 1380, diffusion layer 1390, and/or bumps 1370. Fresnel lens 1310 may include any combination of diffuser 1380, diffusion layer 1390, and/or bumps 1370.

Figure 14 illustrates an exemplary bump 1410 scattering light rather than coherently reflecting light. Rays 1420, 1430, and 1440 are substantially parallel to each
15 other and impinge on bump 1410. If rays 1420, 1430, and 1440 impinge on a flat surface they may be reflected coherently with respect to one another and are more likely, therefore, to create a stray image. Since the surface of bump 1410 is curved, however, each ray has a different angle of incidence with respect to bump 1410. Therefore, bump 1410 scatters rays 1420, 1430, and 1440. Rays 1450, 1460, and 1470 illustrate the
20 scattering effect of bump 1410.

Figure 15 illustrates an exemplary diffusion layer 1510 diffusing light that might otherwise form a stray image. Ray 1520 impinges on Fresnel lens 1530. Ray 1520

travels through diffusion layer 1510 and is diffused slightly into rays 1540, 1542, and 1544. Light from rays 1540, 1542, and 1544 may reflect off of the flat output surface of Fresnel lens 1530.

Ray 1550 is an exemplary ray reflecting off of the flat output surface of Fresnel lens 1530. Ray 1550 travels through diffusion layer 1510 and is diffused into rays 1560, 1562, and 1564. If rays 1560, 1562, and 1564 return to Fresnel lens 1530 they are widely separated and will not form a visible stray image.

EXEMPLARY FRESNEL EQUATION

Figure 16 illustrates the relationship between face angle (γ) and output ray angle (β), according to an embodiment of the invention. As shown in Figure 16, input light 1610 reaches Fresnel lens 1600 with an input ray angle theta (θ). The groove angle for the illustrated zone of Fresnel lens 1600 is shown by angle lambda (λ). As previously discussed in connection with Figure 6a through Figure 8, Fresnel lens 1600 may have more than one zone and each zone may have a different groove angle. The various zones of Fresnel lens 1600 may be defined by distances (R) from the center of the Fresnel lens (e.g., the center of Fresnel lens 600, shown in Figure 6a). Table 1 provides a zone equation for the illustrated embodiment of the invention. The zone equation expresses face angle (γ) in terms of the refraction angle, output ray angle (β), and groove angle (λ).

Table 1

First zone	
Minimum radius	R=245
Maximum radius	R=1230
Zone equation	$\gamma = \tan^{-1} \left(\frac{n \sin \{\beta' + \lambda\} + \sin(\theta + \lambda)}{n \cos \{\beta' + \lambda\} - \cos(\theta + \lambda)} \right) + \lambda - \frac{\pi}{2}$
Equation coefficients	$n = 1.55$ $\beta' = \sin^{-1}(\sin \beta / n)$
Groove angle (λ)	38°

Equation 2 describes how output ray angle (β) varies with the radial distance R, in an embodiment of the invention. Equation 2 is expressed as a spline equation. Spline equations are well known to those of ordinary skill in the art.

Equation 2.
$$\beta = \beta_1 + \sum_{k=1}^4 \Delta_k \left[\left\{ 1 + \left(1 + \frac{R - R_0}{R_5 - R_0} - \frac{R_k - R_0}{R_5 - R_0} \right)^m \right\}^{\frac{1}{m}} - 1 \right], \text{ where}$$

$$\Delta_1 = \frac{\beta_2 - \beta_1}{\frac{R_2 - R_0}{R_5 - R_0} - \frac{R_1 - R_0}{R_5 - R_0}} \text{ and } \Delta_k = \frac{\beta_{k+1} - \beta_k}{\frac{R_{k+1} - R_0}{R_5 - R_0} - \frac{R_k - R_0}{R_5 - R_0}} - \frac{\beta_k - \beta_{k-1}}{\frac{R_k - R_0}{R_5 - R_0} - \frac{R_{k-1} - R_0}{R_5 - R_0}}.$$

Table 2 provides the coefficients for equation 2 in an exemplary embodiment of the invention where m is 16 and R_0 is 230 millimeters.

Table 2

k	1	2	3	4	5
R [mm]	260	300	650	950	1232
β [°]	0	0	0	5.5	8.5

Figure 17 provides an exemplary illustration of face angle (γ) and output ray angle (β) varying as a function of radial distance (R) from the center of a Fresnel lens,

according to an embodiment of the invention. As illustrated in Figure 17, face angle (γ) is nonzero in a region close to the center of the Fresnel lens and approaches zero as the radial distance from the center of the Fresnel lens increases. In contrast, output ray angle (β) is nearly zero for small values of the radial distance R and increases as the value of R increases. Thus, in the illustrated embodiment output ray angle (β) is substantially close to zero (e.g., $\pm 10^\circ$) for values of R corresponding to the center of the Fresnel lens and increases for values of R corresponding to the corners of the Fresnel lens. In alternative embodiments, the relationships between face angle (γ), output ray angle (β), and radial distance from the center of a Fresnel lens (R) may be different than those illustrated in Figure 17.

The Relationship Between the Screen Diagonal Length and the Focal Distance of the Fresnel Lens

Figure 18 is a front view of screen 1800. Reference numeral 1810 illustrates the screen diagonal of screen 1800. Screen diagonal refers to the distance from one corner of screen 1800 to the opposite corner of the screen. In an embodiment, the term screen diagonal refers to the diagonal length of the viewable portion of screen 1800. In an alternative embodiment, the term screen diagonal refers to the diagonal length of the actual size of screen 1800. Screen 1800 is a Fresnel lens, in an embodiment of the invention.

Reference numerals 1820 and 1830, respectively, illustrate the width and height of screen 1800. The ratio of width 1820 to height 1830 defines the aspect ratio of screen 1800. In an embodiment, the aspect ratio of screen 1800 is 16:9. In an alternative embodiment, the aspect ratio of screen 1800 is 4:3. Screen 1800 may have an aspect ratio
5 other than 16:9 and 4:3.

Figure 19 illustrates rear projection display device 1900. Rear projection display device 1900 includes wide-angle lens system 1910 and screen 1920. In an embodiment, screen 1920 is a Fresnel lens. Focal distance 1930 represents the focal length of Fresnel lens 1920. The term focal length refers to the distance from the optical center of Fresnel
10 lens 1920 to focal point 1940. The term focal point may refer to the spot at which impinging rays converge to a common point or focus. Aberrated rays may also form a focal point. The term “circle of least confusion” refers to a focal point formed by aberrated rays. The focal point is usually placed near the pupil of a projection lens (e.g, the pupil of the projection lens of wide-angle lens system 1910.

15 Focal distance 1930 may be used to express the thinness of rear projection display device 1900. For example, the thinness of rear projection display device 1900 may be expressed by the ratio of the screen diagonal of Fresnel lens 1920 to focal distance 1930. In an embodiment in which the screen diagonal is 60 inches, the ratio of the screen diagonal to focal distance 1930 is approximately 3.0. In an alternative embodiment of the
20 invention in which the screen diagonal is 70 inches, the ratio of screen diagonal to Fresnel focal distance is approximately 4.1. The term “approximately equal to” refers to a value that is within ten percent of the provided value.

Reference in the specification to “one embodiment” or “an embodiment” means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the invention. The appearances of the phrase “in one embodiment” in various places in the specification are not necessarily
5 all referring to the same embodiment.

In the foregoing specification, the invention has been described with reference to specific embodiments thereof. It will, however, be evident that various modifications and changes can be made thereto without departing from the broader spirit and scope of the invention. The specification and drawings are, accordingly, to be regarded in an
10 illustrative rather than a restrictive sense.